MICROMECHANISMS OF FRACTURE IN PRECRACKED WELDED SPECIMENS

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ABSTRACT

Fatigue precracked specimens are used for more precise evaluation of crack resistance behaviour of different regions of heat-affected-zone and weld metal of quenched and tempered high-strength steel. J integral value for maximum load and final stretch zone width served as crack resistance measure in testing; performed at room temperature and at -60°C. Significant heterogeneity of microstructure and of crack resistance properties had been found in different regions of heat-affected-zone, and the lowest values are found in weld metal. Crack resistance parameters are distributed across heat-affected-zone as regularly decreased, starting from fusion line, when tested -60°C, but irregularity in distribution is found at room temperature. Satisfactory correspondence between J integral and final stretch zone width is found.

KEY WORDS

Heat-affected-zone (HAZ), toughness, stretch zone width (SZW), J integral, crack-opening-displacement (COD)

1. INTRODUCTION

The successful use of weldable quenched and tempered high strength steel, developed for low temperature application, depends on the degradation rate of base metal (BM) properties in heat-affected-zone (HAZ) during welding. Weld metal (WM) can be the locations of reduced toughness, compared to BM, with the nil ductility transition temperature shifted to higher values. The impact toughness of welded joint is usually evaluated by Charpy V specimens testing, with the notch tip positioned in WM and different regions of HAZ. However, the root radius of V notch, considered as a stress raiser, is to large in comparison to the entire HAZ, and for this reason stress state around it can not produce required plane strain condition. Having in mind the HAZ heterogeneity in structure and mechanical properties, significant scatter in impact toughness values could be expected in Charpy V testing /1/. The detailed analysis of HAZ can reveal the regions of different microstructures, which depends on temperature gradient in HAZ during welding.

The special problem is connected with local brittle zones (LBZ) and local soft zones (LSZ) /2/, with reduced toughness and crack resistance properties, representing the weak points in HAZ and welded joint. Compared to the fusion line, LBZ can be found in the region of higher temperature (close to fusion line), and LSZ are mainly distributed in the region of lower temperature (close to unaffected base metal). In order to obtain critical LBZ and LSZ's as small as possible, the entire HAZ has to be of limited size. In the case of quenched and tempered high strength steels, this is possible to achieve by precisely defined welding technology, including limited heat input.

It had been learned from previous tests of impact toughness with Charpy V specimens that resulting scatter is connected with the large notch root radius and its tip precise position when compared with the different microstructures in HAZ, even in the case of testing at -60°C, the temperature bellow the specified nil ductility transition temperature for tested quenched and tempered NIOMOL 490 steel /1/. For better understanding crack behaviour in HAZ and its critical regions, fatigue precracked specimens could be applied /3,4/. With this type of specimen J integral and its critical value can be evaluated as a measure of crack resistance and toughness. In addition, final stretch zone width (SZW), that preceded final fracture, can also be measured. Comparison of J integral value and SZW for WM and different regions of HAZ can help in understanding of crack properties and significance for practical application of weldable quenched and tempered high strength steels.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

Material description

The material investigated was a 30 mm thick plate of NIOMOL 490 steel with chemical composition given in Table 1 and tensile properties presented in Table 2.

Table 1. Composition of NIOMOL 490 steel (weight %)

C	Si	Mn	P	S	Cu	Nb	Cr	Ni	Mo
0.06	0.32	1.01	0.014	0.004	0.3	0.06	0.17	0.15	0.23

Table 2. Tensile properties of NIOMOL 490 steel

Yield strength, MPa	Tensile strength, MPa	Elongation, %
490	611	27

Welding conditions

In order to obtain convenient form of HAZ for this experiment, with one side normal to the plate surface, welded joint had been shaped with K preparation for multipass manual arc welding, using basic coated electrodes of 3.25 mm in diameter. The welding regime parameters were: welding current 130 A, arc voltage 23 V, welding speed 4 mm/s with heat input of about 7 kJ/cm.

Specimens

The specimens were produced according to ASTM E812 as precracked Charpy V specimens in the form of SE(B) specimen. Charpy V specimens were prepared with V notch positioned in WM, at fusion line and selected positions in heat-affected-zone (at 0.2, 0.5 and 0.8 mm distance from fusion line), according to scheme in Fig. 1. After machining the notch, fatigue cracks were produced on high frequency pulsating machine Amsler, 100kN, at 180 Hz, following the instructions given in ASTM E813.

Experiments

Experiments were performed on a Wolpert hydraulic machine, applying a single specimen elastic compliance technique for J integral evaluation, at room temperature and at -60°C. Load - load line displacement for J integral calculation and load - crack opening displacement (COD) for crack extension evaluation were plotted according to ASTM E813 and ASTM E1152. The test at -60°C was performed in the recipient of convenient design, in which specimen was partly emerged in petrol ether and liquid nitrogen solution, with V notch and crack on the upper side. In this way COD gauge could be applied safely, out of the liquid solution

The fracture surfaces were studied on all tested specimens by scanning electron microscope in order to get closer insight in microstructure dependence of crack resistance properties. For the measurement of final stretch zone width the fracture surface was titled at an angle of about 45° with respect to incident beam.

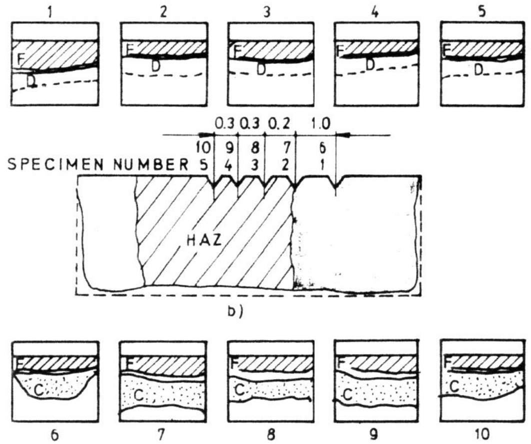


Figure 1. Scheme of crack tip position in welded joint and fracture surface of specimens (F - fatigue precrack, C - cleavage fracture, D - ductile fracture) Specimens 1 and 6 are in WM , 2 and 7 at the fusion line, specimens 3 and 8 in HAZ at 0.2 mm distance from fusion line, 4 and 9 in HAZ at 0.5 mm, and specimens 5 and 10 at 0.8 mm distance from fusion line. Specimens 1 - 5 tested at room temperature, specimens 6 - 10 tested at -60°C.

3. RESULTS AND DISCUSSION

Typical plots load vs. COD at room temperature and at -60°C are presented in Fig. 2. It is to be noticed that smooth shape of plot in Fig. 2a, obtained at room temperature, corresponds to blunting and stable crack growth during the experiment, exhibiting ductile behaviour of final fracture (in Fig. 1 designed by D). However, the specimens were broken in a brittle manner when tested at -60°C, with cleavage as final fracture (in Fig. 1 designed by C). Final stretch zone of different size for different crack tip positions preceded cleavage fracture. Point A in Fig. 2b corresponds to the load at which pop-in in cleavage fracture had been arrested (compare part designed by C in Fig. 1). In this way two typical loads could be defined for the test at -60°C. The first one corresponded to maximum load P_{max}, and the second to the load of arrested pop-in, P_A, as given in Table 3.

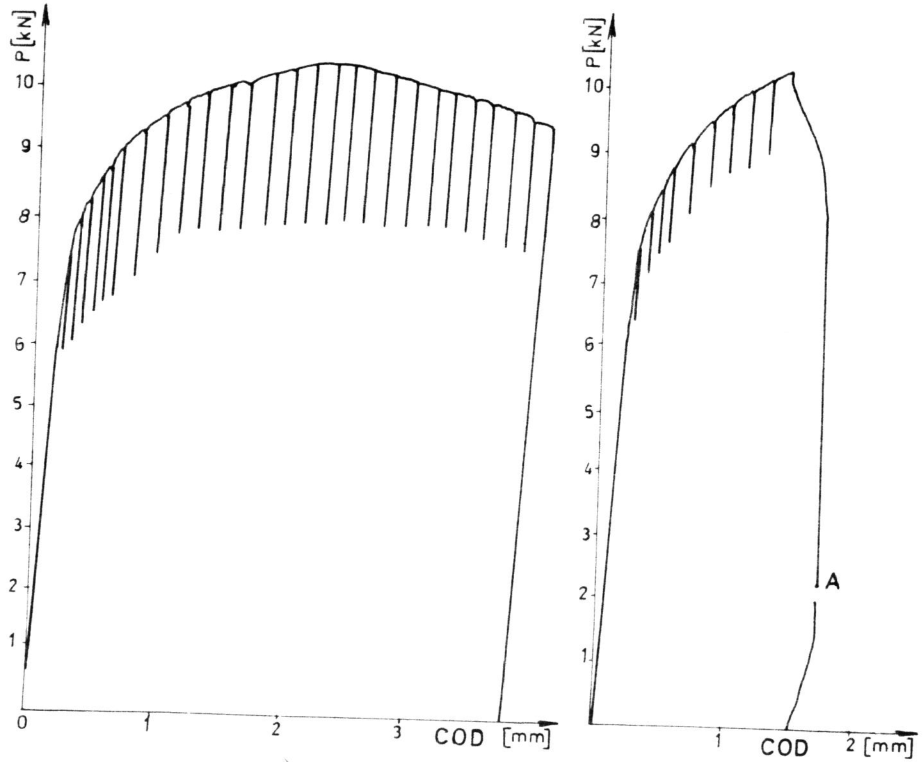


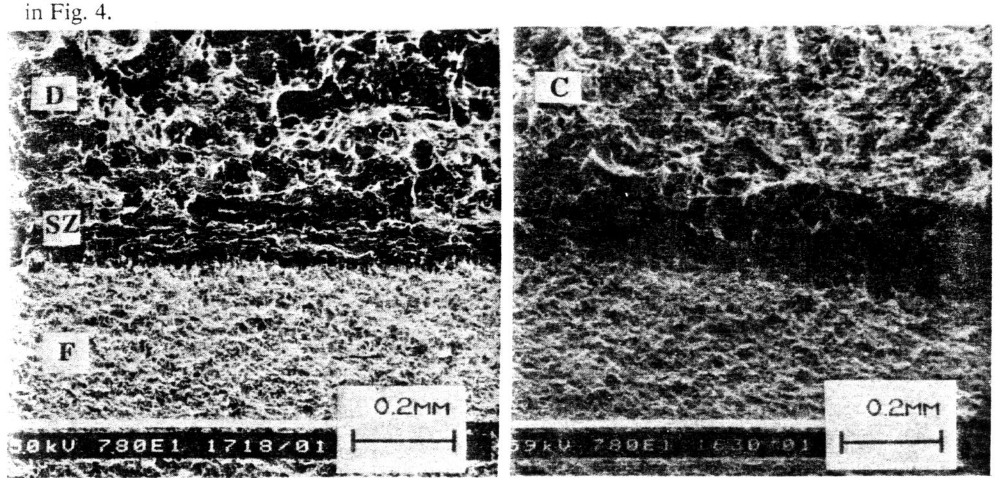
Figure 2. Typical plot load - COD for specimen 4, tested at room temperature (a) and for specimen 9, tested at -60°C (b)

The results of calculated bending crack strength, J integral for maximum load and of final stretch zone width are listed in Table 3.

Table 3. Experimental results

Specimen number	Test tempe-rature °C	Fatigue precrack a_o, mm	Maximum load P_{max}, kN	Load at arrested pop-in P_A, kN	Crack strength σ_s, MPa	J integral at maximum load J, kJ/m^2	Stretch zone width SZW, mm
1	20	3.07	5.65	-	827	403	0.140
2	20	4.03	8.35	-	1647	680	0.290
3	20	4.16	9.50	-	1741	930	0.560
4	20	3.10	10.70	-	1745	650	0.190
5	20	3.77	8.10	-	1467	787	0.310
6	-60	3.00	10.90	5.4	1564	100	0.160
7	-60	4.10	9.20	2.5	1858	704	0.475
8	-60	3.60	9.80	3.8	1682	605	0.437
9	-60	3.29	10.70	2.1	1671	318	0.231
10	-60	3.52	9.60	4.3	1607	239	0.121

Typical view of stretch zone is presented in Fig. 3 for specimen 4, tested at room temperature (a), and for specimen 9, tested at -60°C (b). Stretch - cleavage transition region of fracture for specimen 8, with high value of final stretch zone width, is presented in Fig. 4.



a) b)

Figure 3. Final stretch zone for specimen 4, tested at room temperature (a) and for specimen 9, tested at -60°C (b) (F - fatigue precrack, SZ - stretch zone, D - ductile fracture, C - cleavage fracture)

Bending crack strength σ_s (MPa) is calculated according to ASTM E812 for fatigue precrack length a_o (mm) and maximum load P_{max} (kN) given in Table 3:

$$\sigma_s = \frac{1.5 P_{max} S}{B(W - a_i)^2} \qquad (1)$$

where S (mm) is a span, W (mm) specimen width and B (mm) specimen thickness.

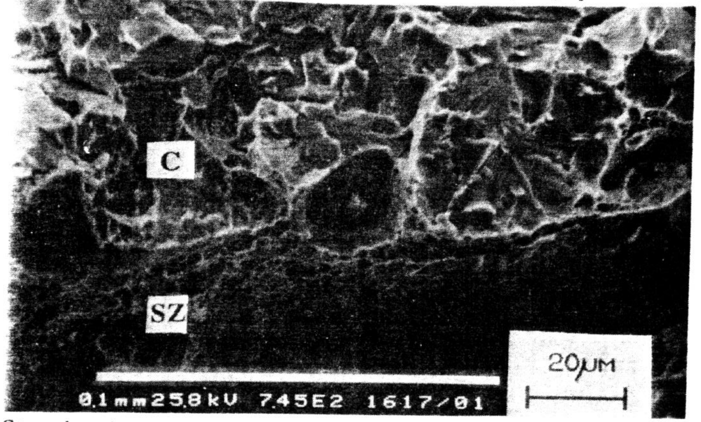


Figure 4. Stretch - cleavage transition region in specimen 8 (SZ - stretch zone, C -cleavage)

In this experiment J integral value, corresponding to maximum load, had been calculated according to ASTM E813 from elastic J_{el} and plastic J_{pl} components:

$$J = J_{el} + J_{pl} \qquad (2)$$

The value J_{el} can be calculated according to the formulae from ASTM E399, for initial crack length a_o. Plastic component J_{pl} corresponds to the energy, presented by the area A_{PL} (mm^2) under load - load line displacement curve. For each point *i*:

$$J_{pl} = \frac{2 A_{PL}}{B b_i} \qquad (3)$$

where $b_i = W - a_i$ (mm) stands for actual ligament.

Starting with initial compliance value, corresponding to the initial crack size a_o, the changes in unloading slopes in load - COD record enable to evaluate crack growth for each step and actual crack length a_i.

There is no significant difference in crack strength values at fusion line, at 0.2 and at 0.5 mm distance from fusion line in HAZ, at room temperature and at -60°C. Significant drop in crack strength is found in WM, tested at room temperature, and only a slight drop at 0.8 mm distance from fusion line in HAZ. Regular decreasing in crack strength across HAZ is observed at -60°C, with the highest value at fusion line. The lowest crack strength value is found in WM, but the drop is not so significant as in the case of room temperature.

Fracture toughness is expressed here by two parameters: J integral value at maximum load and final stretch zone width. Regular distribution of fracture toughness

Fracture toughness is expressed here by two parameters: J integral value at maximum load and final stretch zone width. Regular distribution of fracture toughness across HAZ at -60°C is obtained in both parameters values, with the highest values at fusion line and the lowest values at 0.8 mm distance from fusion line. For the specimens tested at room temperature irregular distribution is found: the highest values are obtained at 0.2 mm distance from fusion line, the next values corresponded to the position of 0.8 mm distance, followed by the values at fusion line and with the lowest values at 0.5 mm distance in HAZ. Weld metal was the critical region regarding fracture toughness at both testing temperatures, with significantly reduced J integral values compared to other positions and the lowest final stretch zone widths (with the exception of specimen 10).

The differences in J integral values at room temperature and at -60°C at the fusion line and at 0.2 mm distance could be evaluated as small.

The correspondence between values of J integral and final stretch zone width is satisfactory, having in mind the difficulties in testing and measurement procedures.

In order to explain irregular and unexpected results in crack resistance behaviour, obtained in this experiment, the property of fusion line region and next HAZ parts has to be considered. Fusion line is confined by crystallized previously molten weld metal, on one side, and by heat affected, but continuously solid material, on the other side. These two regions are of completely different microstructure. It is possible to propose that in the vicinity of fusion line brittle and tough parts can follow each other in an irregular way. Both J integral and crack strength are values of global character, representing total strain energy, consumed for crack extension, and load applied to net cross section, respectively. High value of crack resistance parameters, accompanied by high strength value, as it is the case at fusion line crack position, tested at -60°C (specimen 7), could be accepted if the portion of tough parts is predominant compared to brittle parts. However, this situation could be changed in the very close distance due to significantly different microstructures, and crack tip slightly shifted in one or in the other direction can cause completely different response of material regarding toughness, e.g. lower values are obtained at fusion line tested at room temperature (specimen 2).

The difference in micro structure and mechanical properties across HAZ, from fusion line to base metal, is the consequence of different temperatures, reached in the considered positions during welding, followed by different phase transformations. The heat-affected-zone width of approximately 2 mm in this case, corresponded to the temperature drop from melt point to about 500°C, containing typical microstructures for temperature ranges (including LBZ and LSZ), with typical crack resistance properties, as it is expressed by the differences in obtained J integral values. In the heat-affected-zone brittle and tough parts can follow each other in an irregular way and crack resistance will depend on the portion of these parts in total fracture surface. When LBZ and LSZ are considered, the temperature distribution law in HAZ during welding and holding time at different temperatures could be important data. The difference in J integral value distribution at room temperature and at -60°C could be attributed to the different micro structures and their relative nil ductility transition temperature in considered positions of HAZ.

Remarkable load value of arrested pop-in, observed for all the specimens tested at -60°C, including that of low toughness (specimens 9 and 10 in HAZ, and specimen 6 in WM), can be taken as a prove of tested steel quality for low temperature application.

Performed fractography using scanning electron microscopy enabled closer insight in micro structure of tested specimens. Final stretch zone is clearly expressed and separated from cleavage fracture on the specimens tested at -60°C (Fig. 3b, Fig.4), so that its width can be easily measured, exhibiting the lowest values in HAZ at 0.8 mm distance and in WM, as it was the case with J integral values. Again, regular decreasing distribution of stretch zone width can be found across HAZ, starting from fusion line. The final stretch zone for the specimens, tested at room temperature, followed by ductile fracture, was not clearly visible and the measured values are not quite sure. The results of stretch zone width measurement at room temperature are irregularly distributed in HAZ, with the highest value in HAZ at 0.2 mm distance from fusion line and the lowest values at 0.5 mm distance and in WM.

4. CONCLUSION

Successful application of high strength micro alloy steels, e. g. quenched and tempered NIOMOL 490 steel (yield strength of 490 MPa), designed for heavy duty welded structures, operating at low temperature, is dependent on the properties of welded joint critical regions. Degradation of toughness, caused by welding, is experimentally analyzed at room temperature and at -60°C, bellow the specified nil ductility transition temperature of the tested steel, by testing of fusion line region and heterogeneous heat-affected-zone parts close to it, using J integral evaluation on precracked specimens by compliance method and final stretch zone measurement on scanning electron microscope. Irregular distribution of J integral across HAZ had been found at room temperature, with the highest value in HAZ at 0.2 mm distance from fusion line, and lowest value at 0.5 mm distance. The largest final stretch zone and highest J integral value for maximum load, as measures of toughness, corresponded to the fusion line region, and by increasing distance from it reduction in toughness value had been found at -60°C. There is no significant difference between highest values at room temperature and at -60°C, but the lowest values differ significantly. The results for weld metal toughness have shown that it could be critical region in welded joint, required detailed analysis. Determination of precise position of critical regions and temperature distribution in HAZ requires further investigation.

REFERENCES

/1/ Kuzmanovic S., at al: Annual report for 1990/91 on the YU-USA project "Fracture Mechanics of Weldments", "Energoinvest", Sarajevo, 1991.

/2/ C. Hafer, R. Twickler, R. Hubo, W. Dahl: Proc. of Int. Conf. WELDING 90, 1990, 155-163.

/3/ J. H. Chen, C. Jan: Mater. Sci. Technol., 1988, vol 4., pp. 732-39

/4/ J. H. Chen, H. Ma, G. Z. Wang: Metal. Trans. A, 1990, vol. 21A, pp 313-20